Solar Technologies – redox cycles for hydrogen and syngas production

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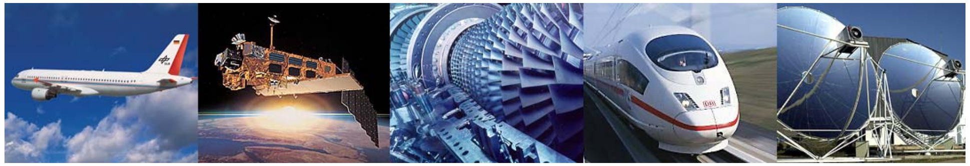
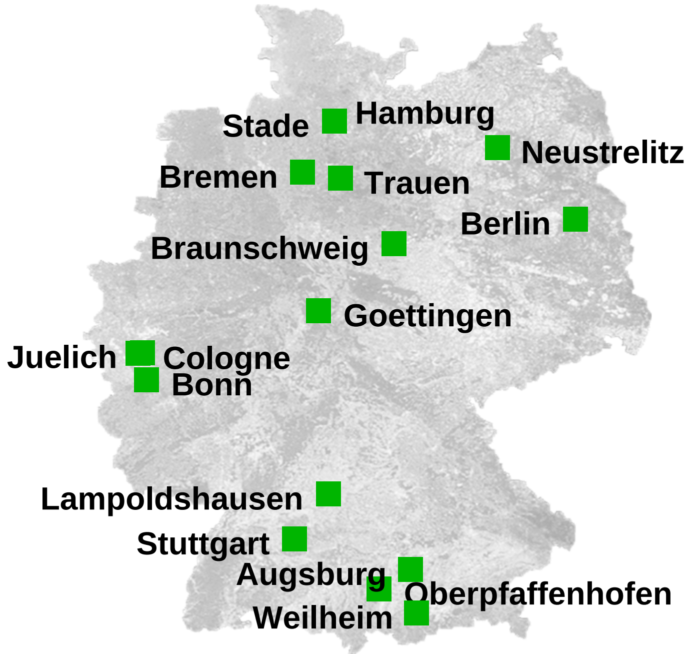
DLR German Aerospace Center

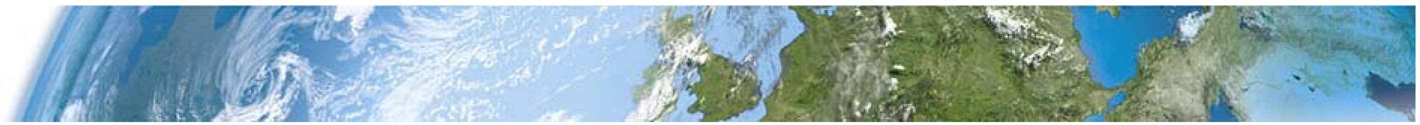


- Research Institution
- Space Agency
- Project Management Agency

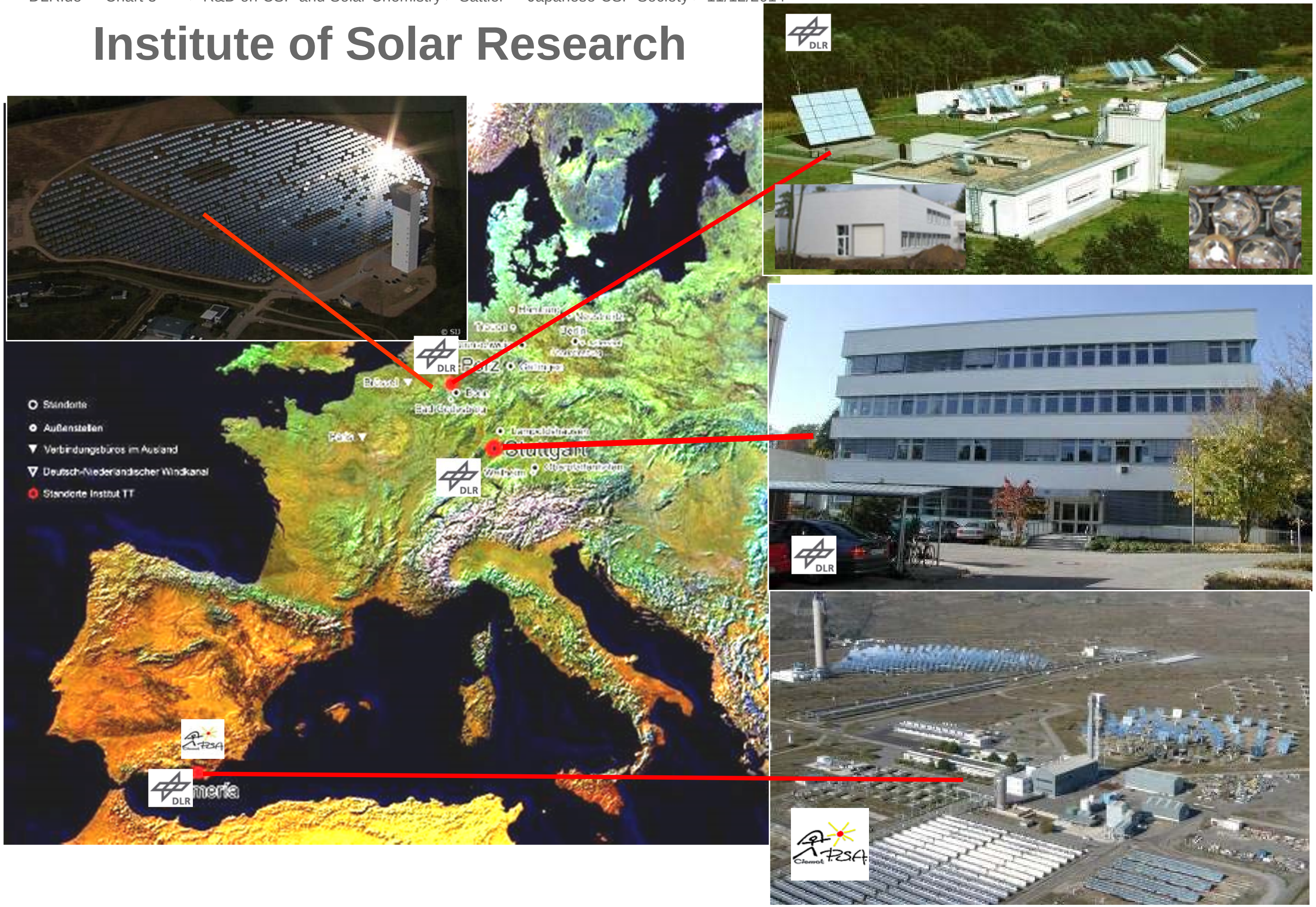
>8000 employees across
32 institutes and facilities at
■ 16 sites.

Offices in Brussels, Paris,
Tokyo and Washington, Almería.

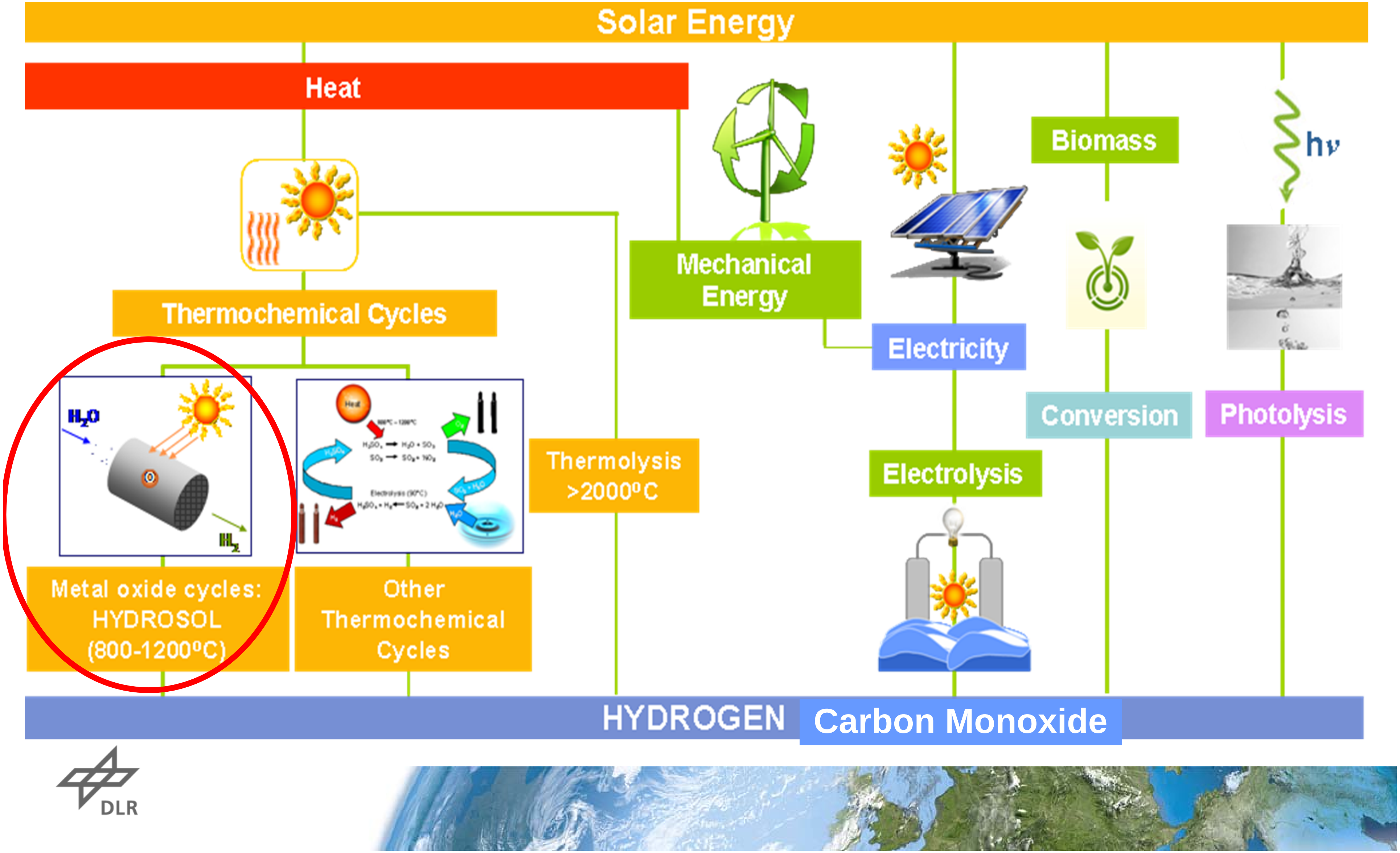




Institute of Solar Research



Solar Pathways from Water or CO_2 to Fuels



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Efficiency comparison for solar hydrogen production from water (Siegel et al., 2013)*

Process	T [°C]	Solar plant	Solar-receiver + power [MW_{th}]	η T/C (HHV)	η Optical	η Receiver	η Annual Efficiency Solar – H_2
Elctrolysis (+solar-thermal power)	NA	Actual Solar tower	Molten Salt 700	30%	57%	83%	13%
High temperature steam electrolysis	850	Future Solar tower	Particle 700	45%	57%	76,2%	20%
Hybrid Sulfur-process	850	Future Solar tower	Particle 700	50%	57%	76%	22%
Hybrid Copper Chlorine-process	600	Future Solar tower	Molten Salt 700	44%	57%	83%	21%
Metaloxide two step Cycle	1800	Future Solar dish	Particle Reactor < 1	52%	77%	62%	25%

**N.P. Siegel, J.E. Miller, I. Ermanoski, R.B. Diver, E.B. Stechel, Ind. Eng.Chem. Res., 2013, 52, 3276-3286.*

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Technical Optimization in all Dimensions necessary

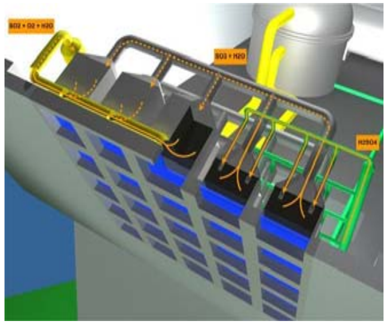
$10^4 – 10^2$ m
Solar Plant

Site

Solar field

Simulation

Environmental impact



$10^2 – 10^1$m
Receiver

Design

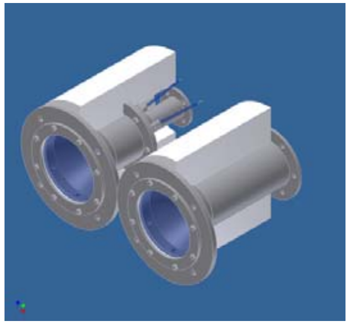
Simulation

Construction

Testing

Next-Generation-

Development



$10^1 – 10^{-2}$m
Receiver-components

Materials

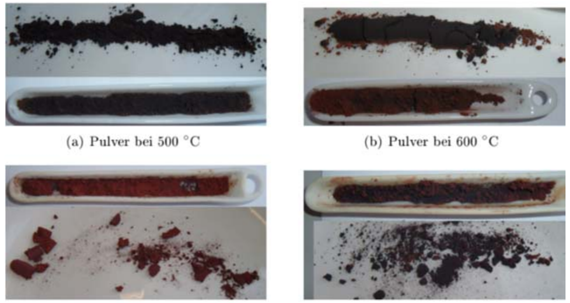
Design

Heat and

Mass transport

Simulation

Testing and Develpment



(a) Pulver bei 500 °C
(b) Pulver bei 600 °C
(c) Pulver bei 800 °C
(d) Pulver bei 900 °C

$10^{-2} – 10^{-8}$ m
Reactive Systems

Simulation

Synthesis

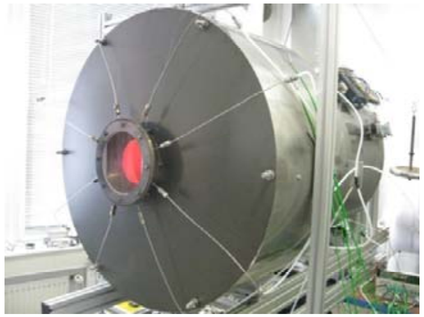
Chemical Charactristics

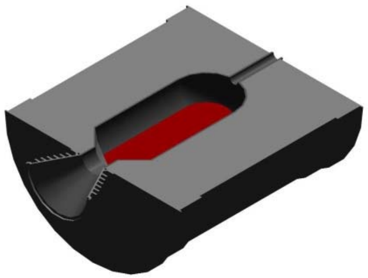
Physical Characteristics

Receiver - Concepts

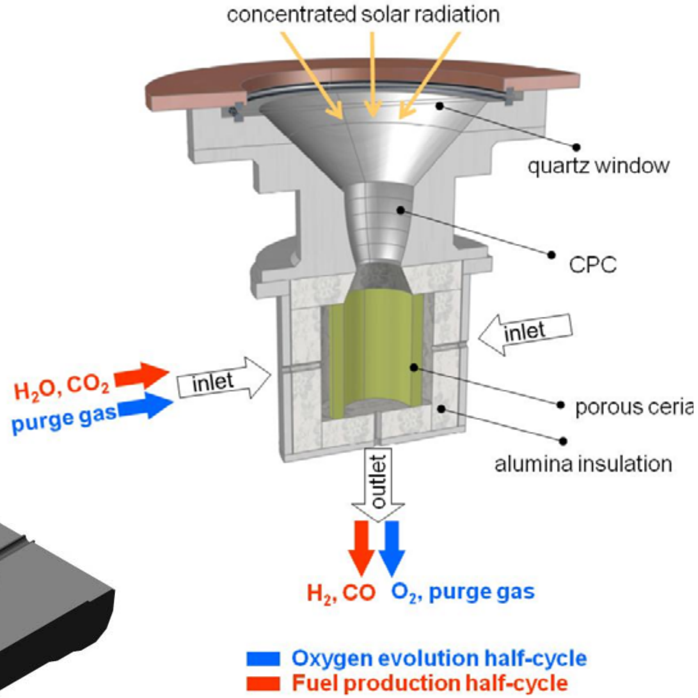
- Challenges:
  - Temperature
  - Corrosion
  - Abrasion
  - Process operation

- Goals:
  - Efficiency
  - Durability
  - Cost

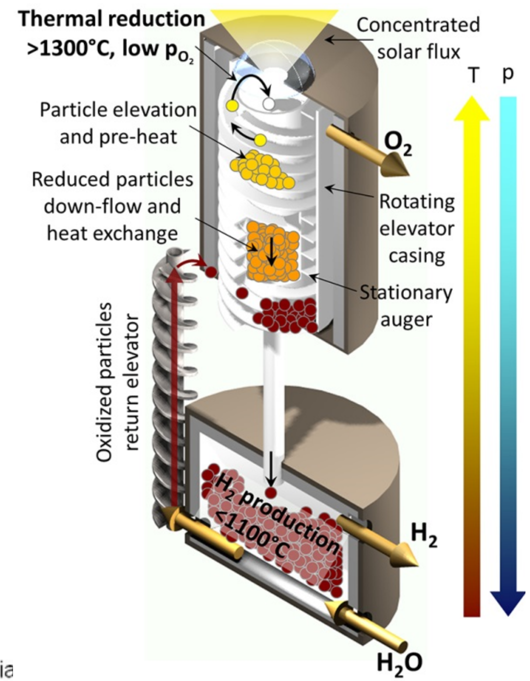




Solar heated Rotary Kiln, DLR



Solar heated Cavity-Gas Receiver
with porous Ceramic structur
A. Steinfeld et al., ETH Zürich

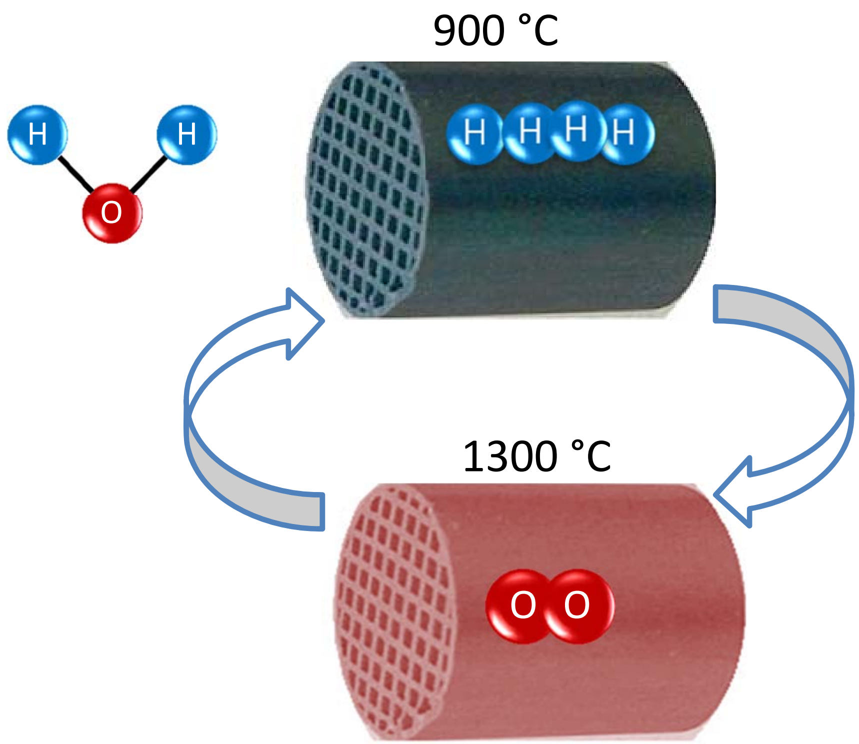


Solar heated Partikel-Receiver
I. Ermanoski et al., Sandia Natl. Lab.

2 Step Thermochemical Cycle for H_2O or CO_2 Splitting Example: HYDROSOL concept

1. Water Splitting

$H_2O + MO_{red} \rightarrow MO_{ox} + H_2$



2. Regeneration

$MO_{ox} \rightarrow MO_{red} + ½\,O_2$

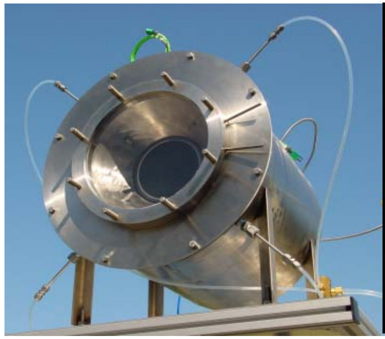
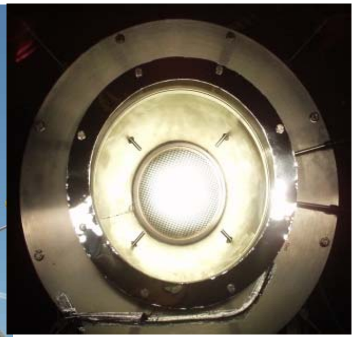
Net Reaction: $H_2O \rightarrow H_2 + ½\,O_2$

PSA
solar tower

Hydrosol technology scale-up


2008:
Pilot reactor
(100 kW)


2005:
Continuous
H_2 production

2004:
First solar
thermochemical
H_2 production

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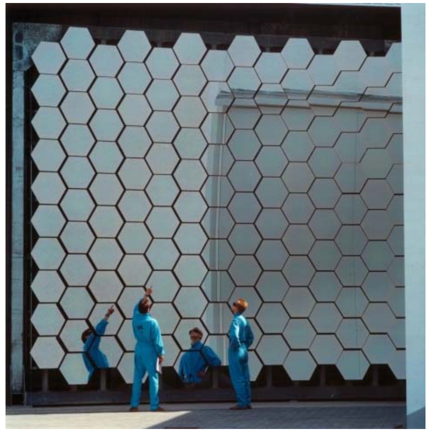
Solar
Furnace



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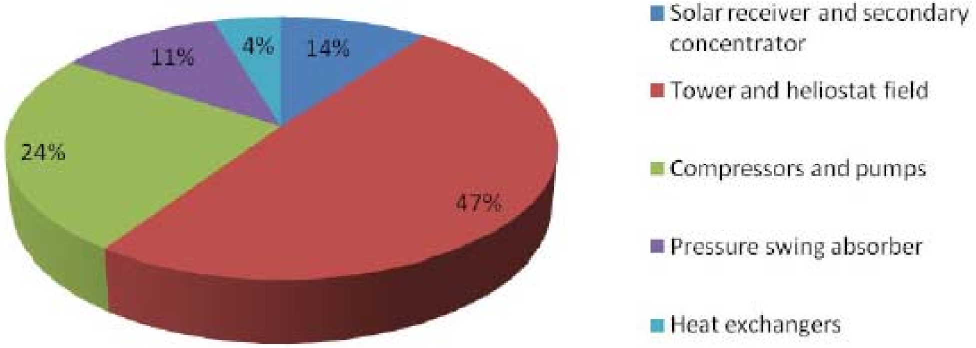
Solar fuels from thermochemical cycles- HYDROSOL 3D project- Main results Economic analysis of the demonstration plant

- Demonstration plant thermal energy input: 1 MW
- Cost calculation of the new designed reactor was carried out.
- Cost calculation of the overall process units was performed.
- More than half of process investment results from the solar system.

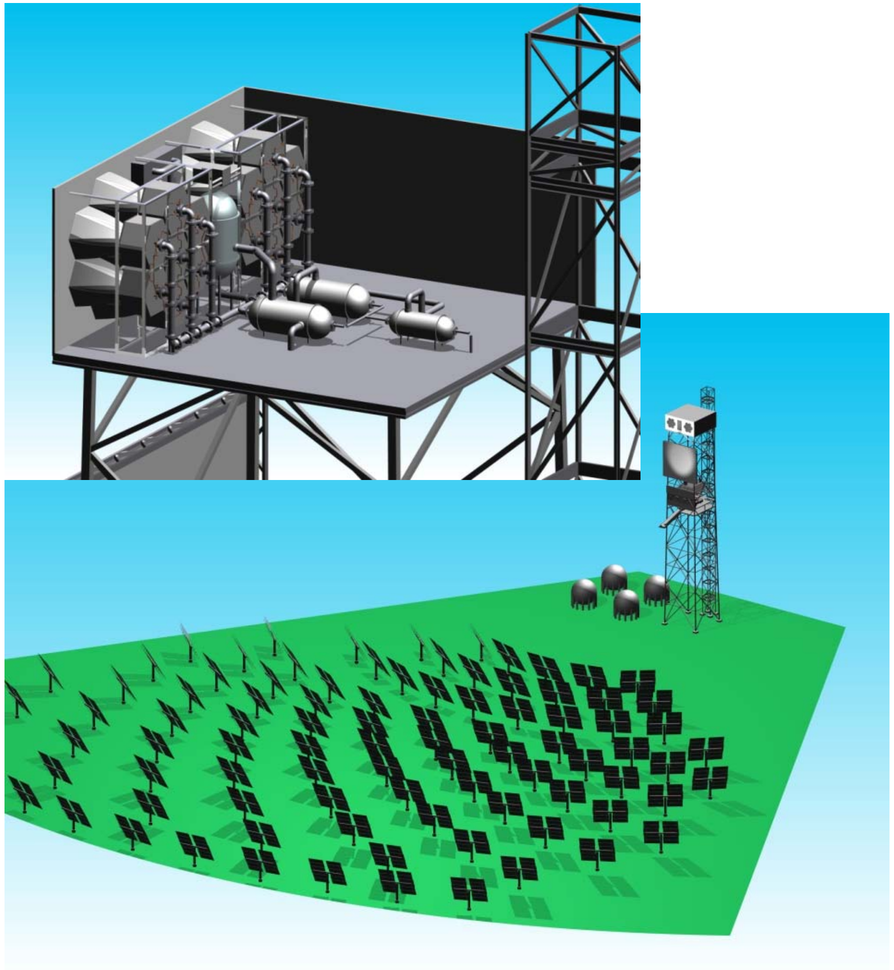
Component	Number of units	Cost per unit [€]	Total Cost [€]
Quartz plates	14	600	8400
Reactor modules	14	3000	42000
Secondary concentrator	14	12000	168000

Solar part incl. receiver-reactor[€]	1,406,847
Pressure swing absorber [€]	265,000
Compressors and pumps [€]	584,054
Heat exchangers [€]	110,493
Total cost [Mio. €]	**2.366**

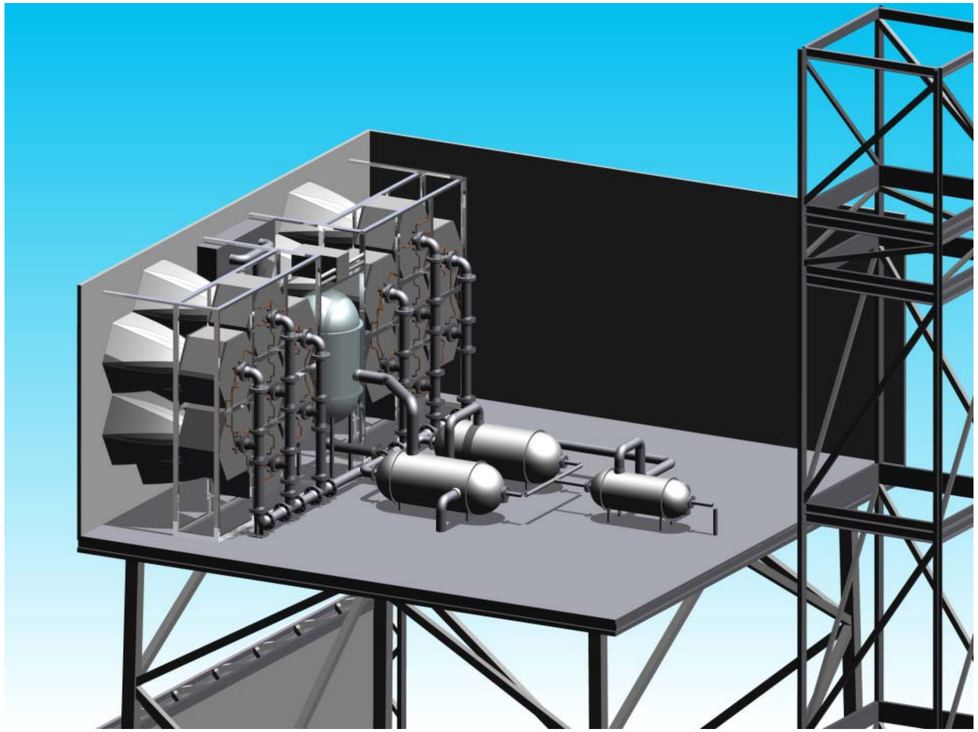


Hydrosol Plant - Design for CRS tower PSA, Spain

- European FCH-JU project
- Partner: APTL (GR), HELPE (GR), CIEMAT (ES), HYGEAR (NL)
- 750 kW_{th} demonstration of thermochemical water splitting
- Location: Plataforma Solar de Almería, Spain, 2015
- Use of all heliostats
- Reactor located on the CRS tower
- Storage tanks and PSA on the ground



HYDROSOL, HYDROSLOL 2, HYDROSOL-3D, HYDROSOL Plant



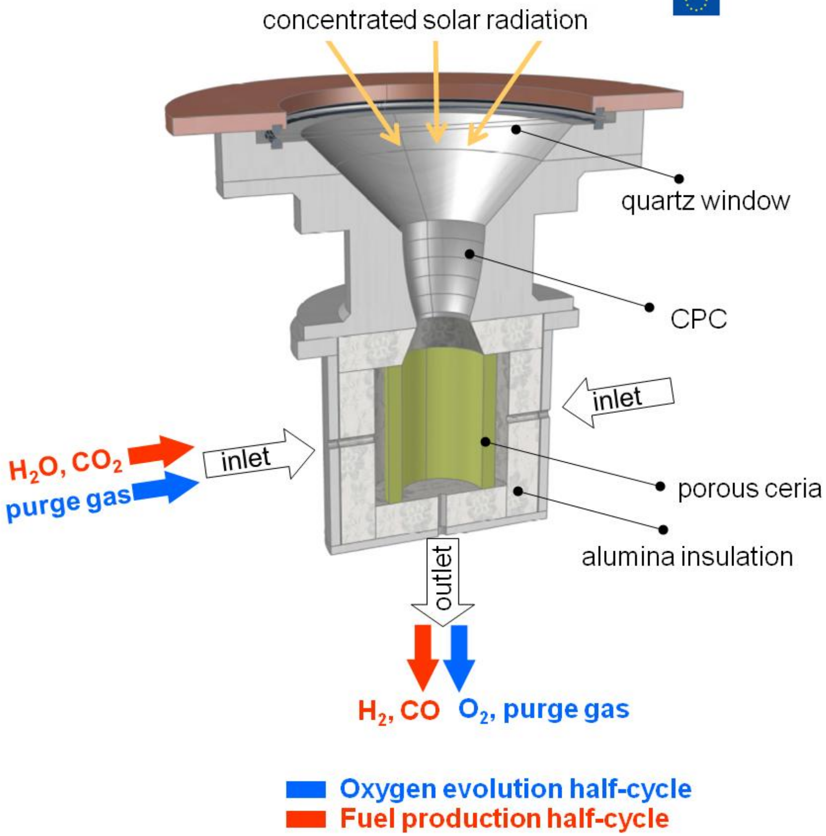
APTL (GR), DLR (DE), CIEMAT (SP), StobbeTech (DK), Johnson Matthey (UK), HyGear (NL), HELPE (GR)

- 2002 Start HYDROSOL, EU FP5
- 2004 First solar hydrogen, DLR
- 2005 Quasi-continuous solar hydrogen, DLR
- 2008 HYDROSOL 2, EU FP6, 100 kW demonstration CRS Tower PSA, Spain
- 2013 HYDROSOL-3D, FCH JU, Design of a 1,5 MW demonstration plant ready
- 2014 HYDROSOL PLANT, FCH JU
- 2016 Operation of the 750 kW Demonstration plant, CRS Tower, PSA, Spain
- 2020 Pre-commercial plant

H_2O/CO_2-Splitting Thermochemical Cycles

Solar Production of Jet Fuel

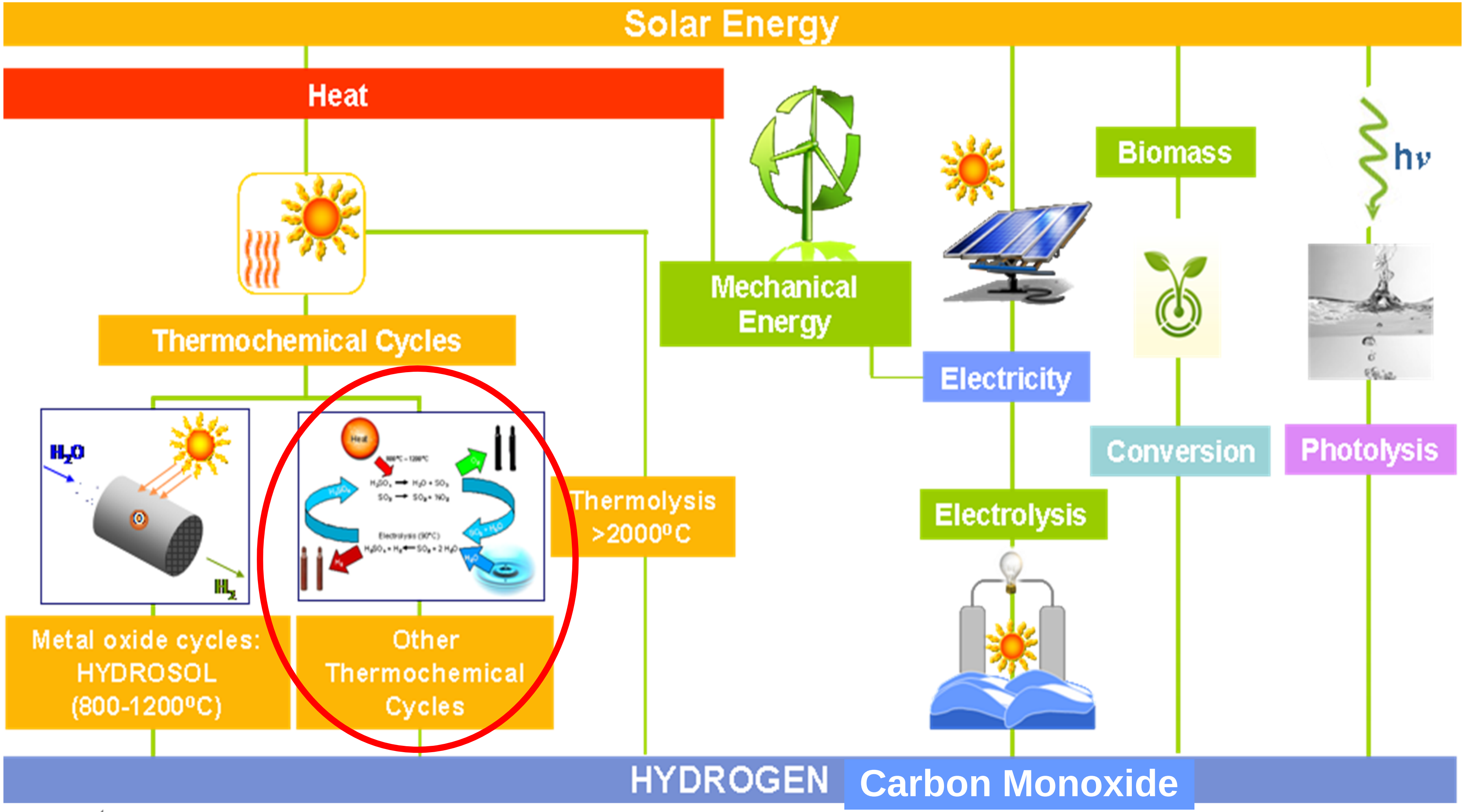
- EU-FP7 Project SOLAR-JET (2011-2015)
- SOLAR-JET aims to ascertain the potential for producing jet fuel from concentrated sunlight, CO_2, and water.
- SOLAR-JET will optimize a two-step solar thermochemical cycle based on ceria redox reactions to produce synthesis gas (syngas) from CO_2 and water, achieving higher solar-to-fuel energy conversion efficiency over current bio and solar fuel processes.
- **First jet fuel produced in Fischer-Tropsch (FT) unit from solar-produced syngas!**



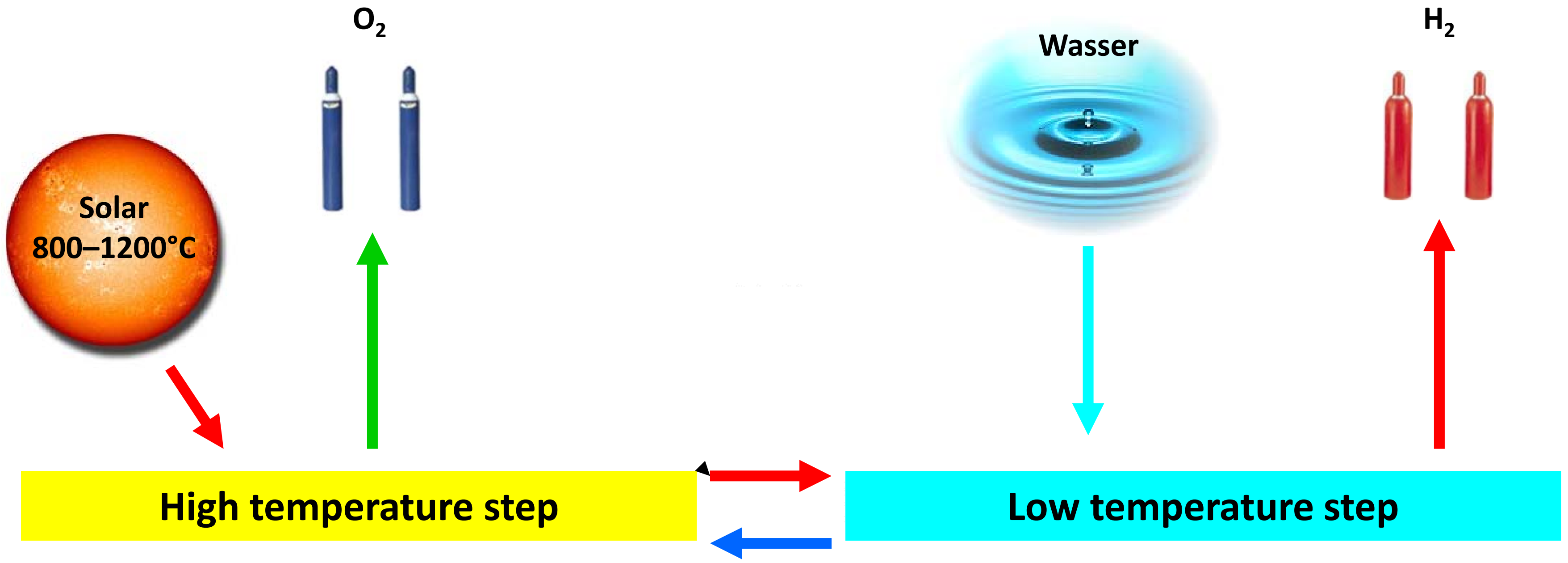
Int. J. Heat & Fluid Flow 29, 315-326, 2008.
Materials 5, 192-209, 2012.

Partners: Bauhaus Luftfahrt (D), ETH (CH), DLR (D), SHELL (NL), ARTTIC (F)
Funding: EC

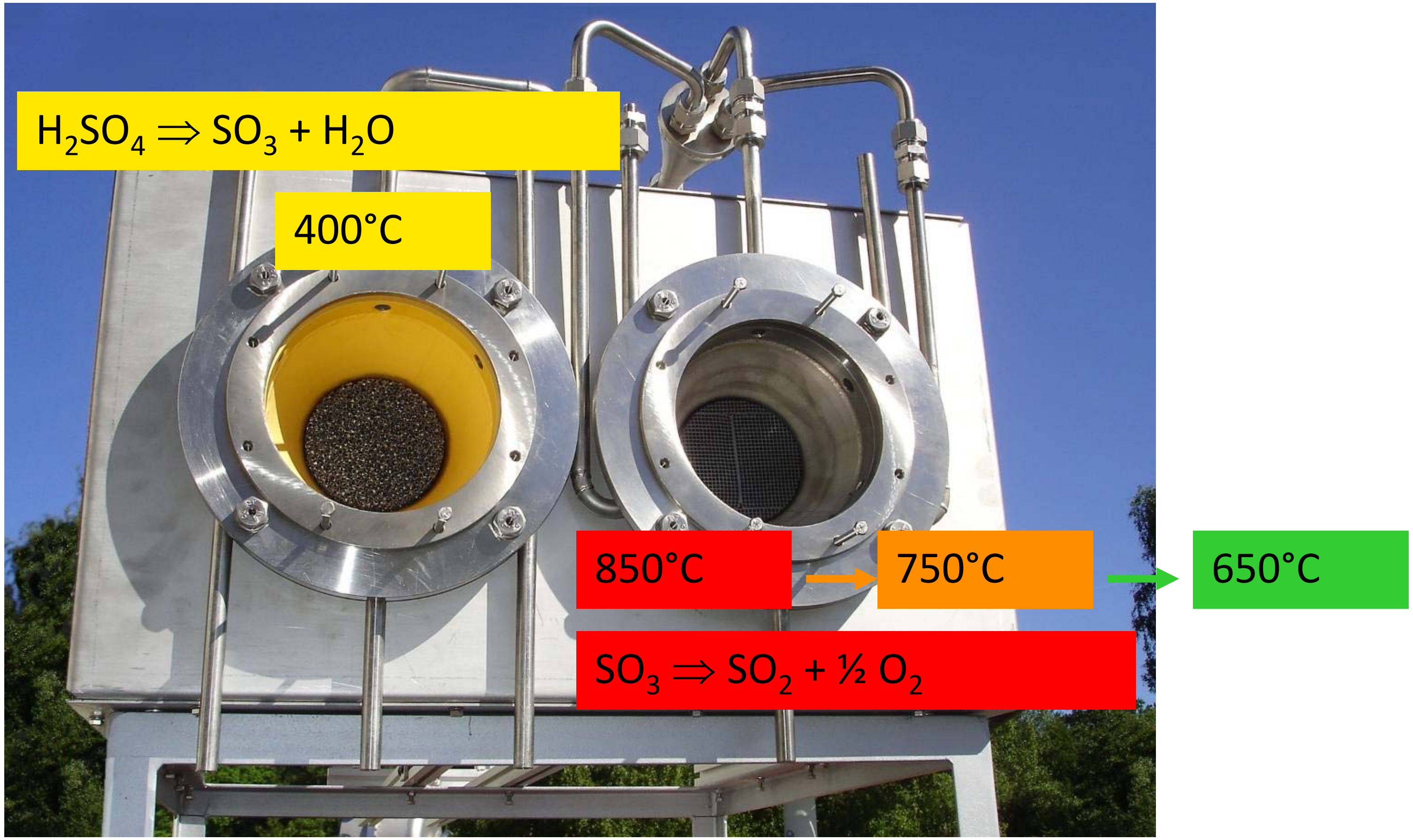
Solar Pathways from Water or CO_2 to Hydrogen



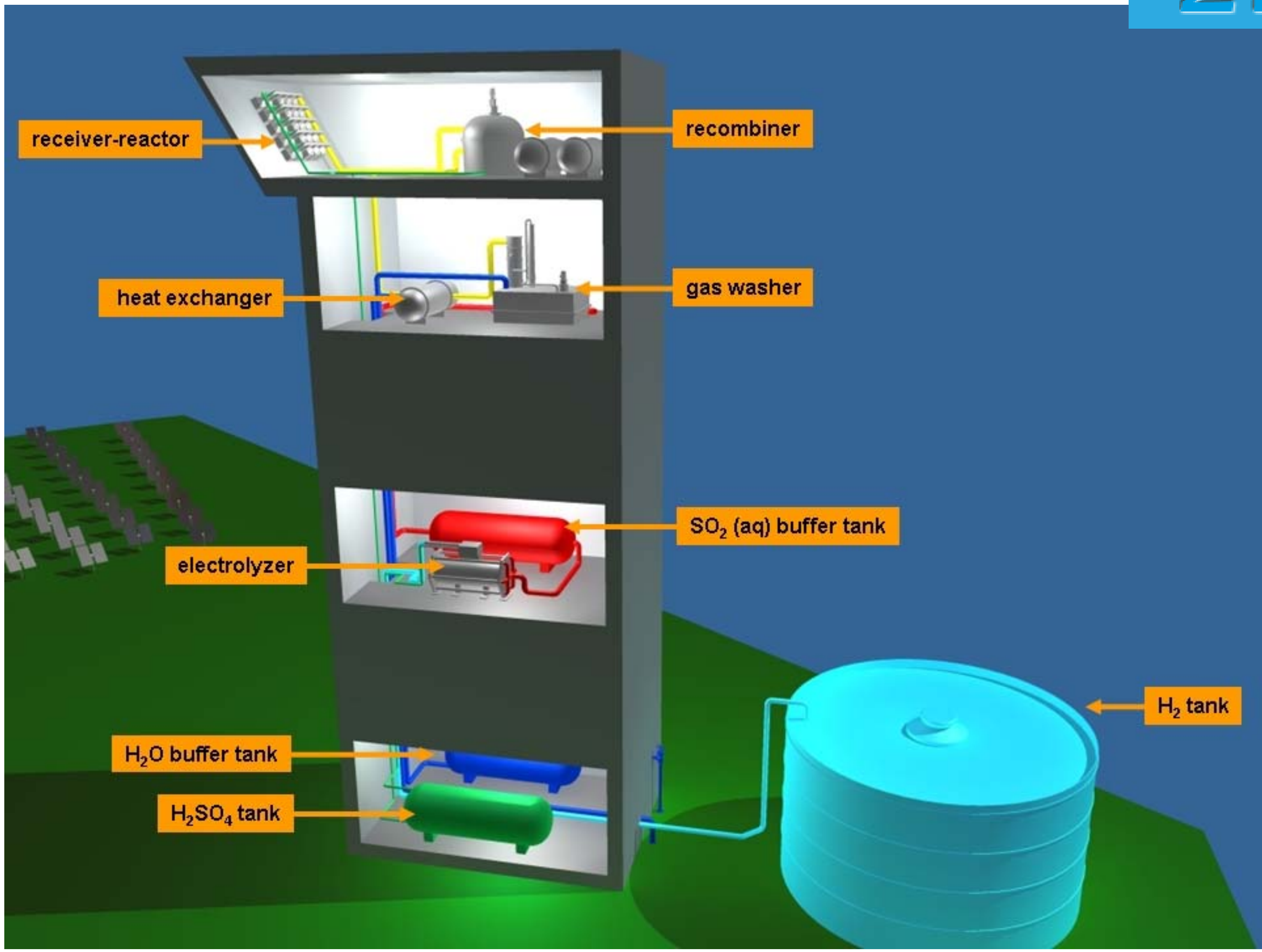
Hybrid Sulfur Cycle (HyS, Westinghouse)



Solar reactor for sulfuric acid decomposition



Implementation into a Solar Tower

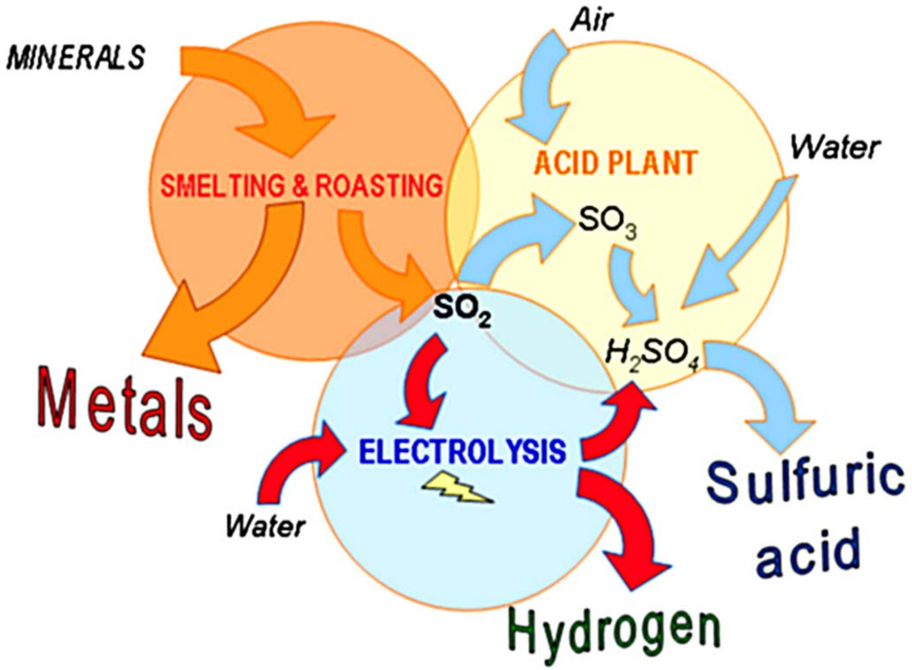


SOL2HY2 – Solar To Hydrogen Hybrid Cycles

https://sol2hy2.eurocoord.com

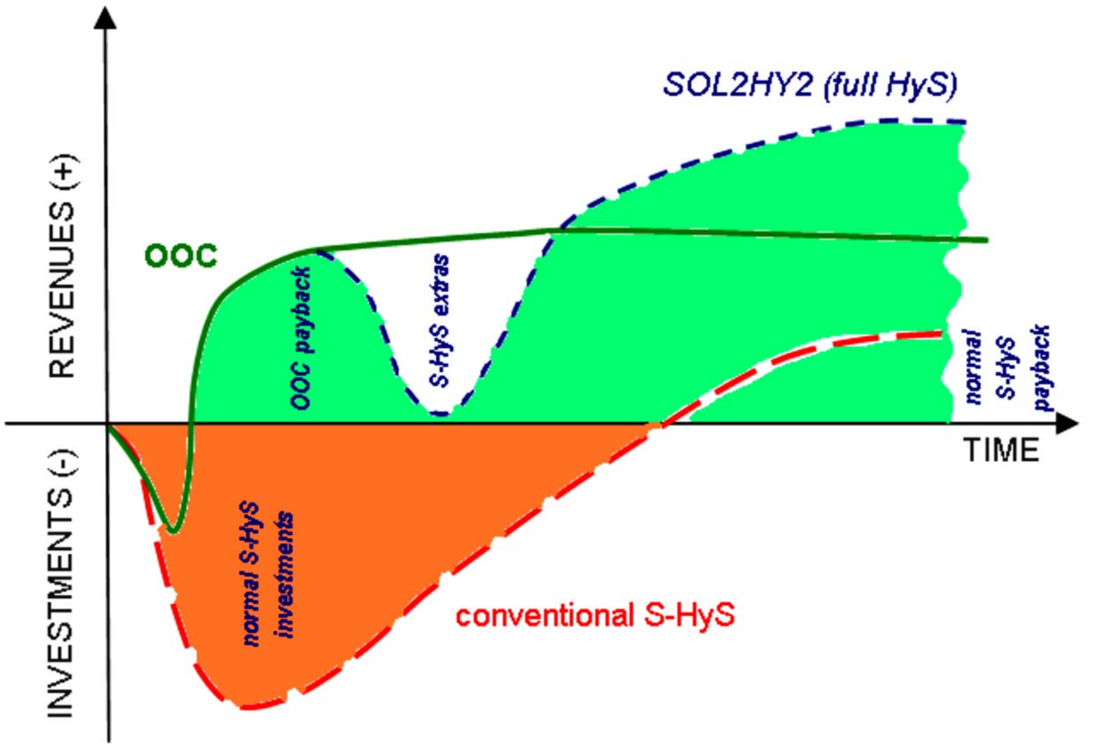
- FCH JU project on the solar driven Utilization of waste SO_2 from fossil sources for co-production of hydrogen and sulphuric acid
- Hybridization by usage of renewable energy for electrolysis
- Partners: EngineSoft (IT), Aalto University (FI), DLR (DE), ENEA (IT), Outotec (FI), Erbicol (CH), Oy Woikoski (FI)
- 100 kW demonstration plant on the solar tower in Jülich, Germany in 2015

Outotec™ Open Cycle (OOC)



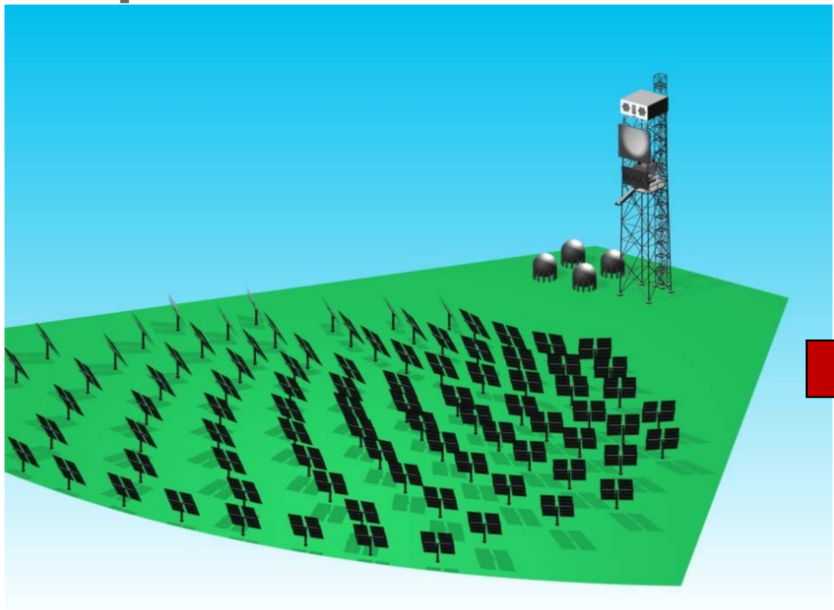
- Utilization of waste SO_2 from fossil sources
- Co-production of hydrogen and sulphuric acid
- Hybridization by renewable energy for electrolysis

Investments vs. revenues

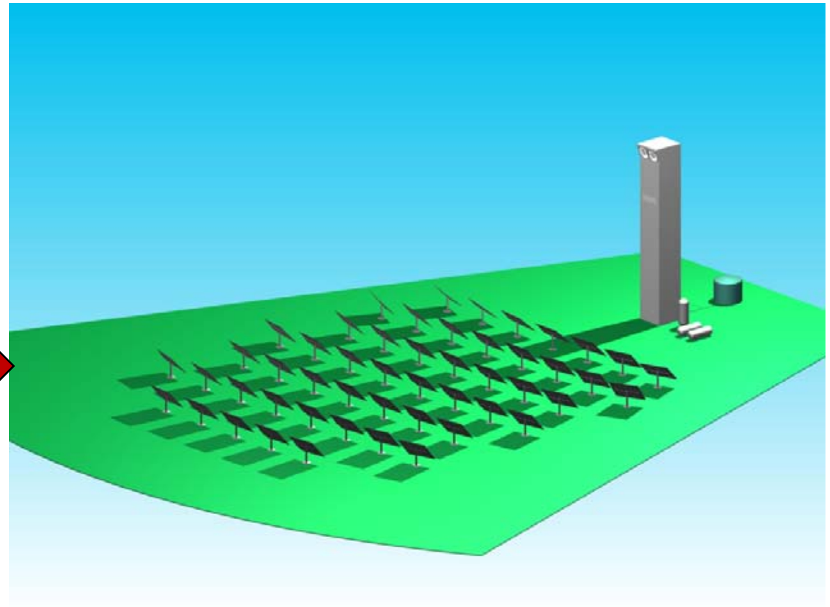


- Reduction of initial investments
- Financing of HyS development by payback of OOC
- Increase of total revenues

Next Step: Pre-commercial application
Specific Solar Fuel Tower needed!



CRS Tower PSA, Spain



Solar Fuels Tower

- High concentration > 1000
- Heliostats fit to receiver size
- Field control adapted to fuel production processes

Thank you very much for your attention!

Promising and well researched Thermochemical Cycles

	Steps	Maximum Temperature (°C)	LHV Efficiency (%)
Sulphur Cycles			
Hybrid Sulphur (Westinghouse, ISPRA Mark 11)	2	900 (1150 without catalyst)	43
Sulphur Iodine (General Atomics, ISPRA Mark 16)	3	900 (1150 without catalyst)	38
Volatile Metal Oxide Cycles			
Zinc/Zinc Oxide	2	1800	45
Hybrid Cadmium		1600	42
Non-volatile Metal Oxide Cycles			
Iron Oxide	2	2200	42
Cerium Oxide	2	2000	68
Ferrites	2	1100 – 1800	43
Low-Temperature Cycles			
Hybrid Copper Chlorine	4	530	39

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